LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

LLNL-PROC-676872

Performance Of An Asperity-Based Kinematic Rupture Model In Ground Motion Simulations Using A Hybrid Approach

A. Pitarka, R. Graves, K. Irikura, H. Miyake, P. Somerville

September 4, 2015

Best Practices in Physics-based Fault Rupture Modesl for Seismic Hazard Assessment in Nuclear Installations
Vienna, Austria
November 18, 2015 through November 20, 2015

Performance Of An Asperity-Based Kinematic Rupture Model In Ground Motion Simulations Using A Hybrid Approach

A. PITARKA[1], R. GRAVES[2], K. IRIKURA[3], H. MIYAKE[4], A. RODGERS[1], P.SOMERVILLE[5]

[1]Lawrence Livermore National Laboratory (LLNL), Livermore, U.S.A.

[2]United States Geological Survey (USGS), Pasadena, U.S.A.

[3]Aichi Institute of Technology, Japan.

[4]University of Tokyo, Tokyo, Japan

[5]AECOM, Los Angeles, U.S.A.

E-mail contact of main author: pitarka1@llnl.gov

Abstract. We analysed the performance of Irikura and Miyake [1] asperity-based rupture model generator (IM2011), in conjunction with the hybrid broadband ground-motion simulation methodology of Graves and Pitarka [2], for simulating ground motion from crustal earthquakes. The objective of our study is to investigate the transportability of the IM2011 to broadband simulation methods used by the Southern California Earthquake Center ground motion simulation platform. We performed broadband (0.1-10Hz) ground motion simulations using rupture models produced with both IM2011 and the rupture generation method of Graves and Pitarka [2], (GP2010). The comparison of the two rupture models was conducted for a series of M6.7 crustal scenario earthquakes. The results of our analyses demonstrate that IM2011 and GP2010 rupture models produce similar ground motion in the considered frequency range of 0.1-10Hz.

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. LLNL-PROC-676872.

Key Words: Ground motion simulation, hybrid approach, rupture model.

1. INTRODUCTION

The broadband ground motion simulation methods of Graves and Pitarka [2] and Irikura and Miyake [1], also known as Irikura and Miyake recipe, use similar time-domain summation schemes. Both methods apply a hybrid approach to compute ground motion acceleration time histories using rupture kinematics for modelling the source, and Green's functions for modelling wave propagation. Earlier versions of Irikura and Miyake method employed empirical Green's functions. However, the scarcity of empirical Green's functions with desired magnitude, distance, focal mechanism and stress drop, motivated modifications of the method that accommodate the use of synthetic Green's functions (e.g.,[3], [4]). These modifications as well as the adoption of improved empirical relations of rupture parameters extended the method's applicability to earthquakes of various types with complex rupture. (e.g. [5],[6],[7],[8],[9]).

In this article we analyse the performance of Irikura and Miyake [1] asperity-based earthquake rupture model (IM2011, hereafter) implemented in the hybrid broadband ground motion simulation methodology of Graves and Pitarka [2]. The Irikura and Miyake [1] hybrid method has been widely used to model and simulate ground motion from earthquakes in Japan. An essential part of the method is its kinematic rupture generation technique, which is based on a deterministic rupture asperity modelling approach. The source model simplicity and efficiency of the IM2011 at reproducing ground motion from earthquakes recorded in Japan makes it attractive to developers and users of the Southern California Earthquake Center Broadband Platform (SCEC BB platform) ([10], [2], [11], [12]). The objective of our study is to investigate the transportability of the IM2011 to broadband simulation methods used by the platform. Here we test it using the Graves and Pitarka [2] method, used by the SCEC BB platform. We performed broadband (0.1-10Hz) ground motion simulations for a series of M6.7 crustal scenario earthquakes and rupture models produced with both IM2011 and rupture generation method of Graves and Pitarka [2], (GP2010 hereafter). In the simulations with the two rupture models we used the same Green's functions, and same high frequency approach for calculating the low-frequency and high-frequency parts of ground motion, respectively.

2. IM2011 and GP2010 Rupture Model Generators

IM2011 is based on the multiple-asperity concept of fault rupture. This concept is an extension of the single-asperity model of Das and Kostrov [13]. IM2011 uses three sets of parameters, named outer, inner and extra fault parameters, to characterize the fault rupture kinematics. The outer parameters characterize the rupture area, and the inner parameters define the spatial and temporal slip distribution computed from estimated stress drop in the asperities and background areas of the fault. The extra fault parameters are the rupture nucleation location, rupture initiation in each asperity, and rupture velocity. The outer and inner fault parameters are linked to the total seismic moment following empirical scaling laws. The number of asperities, total asperity area, and asperity slip contrast follows Somerville et al. [14]. These kinematic rupture parameters have been found to be compatible with those obtained from rupture dynamics modelling of planar faults with multiple asperities [15]. IM2011 has essentially no tuning parameters for same type earthquakes, and in contrast to other rupture generation methods, the rupture kinematics is directly linked to static stress drop [16]. Irikura and Miyake ground-motion simulation method has been validated against recorded ground motion, and extensively used in strong ground simulations of earthquakes in Japan [7]. Since its original inception [17] the method has gone through a series of improvements (e.g. [18],[5],[19]). We direct the interested reader to Irikura and Miyake [1], and Morikawa et al. [7] for a detailed description of the IM2011.

In the IM2011 the asperities are rupture areas with higher stress drop and shorter slip duration. This implies that most of the low and high frequency energy is generated in the asperities areas.

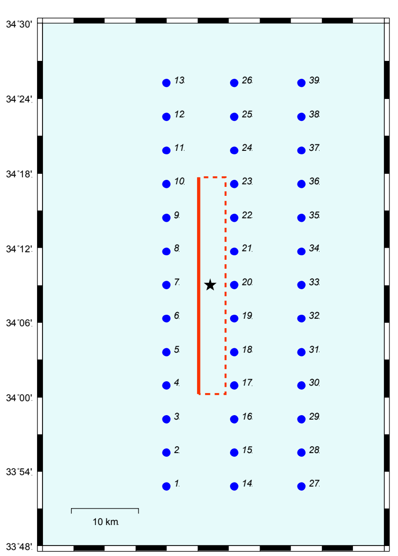

FIG.1. Map of stations location (blue circles) and fault trace (red rectangle). Star indicates the rupture initiation location projected on the free surface.

Since both rupture velocity and slip within each asperity are assumed constant, the resulting high frequency ground motion is mainly controlled by the stress drop, and width and amplitude of the initial pulse in the Kostrov-like slip velocity function adopted by IM2011 [20]. The assumption that the high-frequency ground motion originates only in the asperities is debatable. Inversions of recorded strong-motion data often indicate that areas of high slip are not necessarily areas that produce large amounts of high-frequency energy [21],[9].

GP2010 rupture generator uses variable spatial and temporal kinematic rupture parameters that are calibrated using recorded ground motion and observed rupture kinematics. The rupture process, which is randomly heterogeneous at different scale lengths, controls coherent and incoherent interferences of waves generated at the source. The random perturbations to the rupture kinematics follow well-established rules developed using simulations of past earthquakes. Guided by new data from recent earthquakes GP2010 is subject of continuous improvements [22]. We direct the interested reader to Graves and Pitarka [2] for a detailed description of their simulation method and GP210 rupture model, in particular. Here we are interested to know how these two conceptually different rupture models compare when used in the same broad-band simulation platform, and if necessary, what parameters need to be modified in order to make the IM2011 compatible with the SCEC broadband ground motion simulation platform.

5. Ground Motion Simulations Using IM2011 and GP2010 Rupture Generators

We investigated the performance of IM2011 in conjunction with Graves and Pitarka ground motion simulation method by comparing ground motions simulated with IM2011 and GP2010 rupture models. We considered ground motion from M6.7 scenario earthquakes on a dipping strike slip fault, at hard-rock stations. The fault mechanism and rupture parameters are summarized in Table1. The stations distance from the fault surface projection varies from about 1km to 11 km. Figure 1 shows the fault trace and stations distribution. The rupture is bilateral and it extends from 3 to 19km depth.

The kinematic rupture models generated with IM2011 and GP2010, named Mod1 and GP.0.35, respectively, are shown in Figure 2. Based on the earthquake magnitude, Mod1 has two asperities. The ratio between small and large asperity areas is 6:16. Among several GP2010 rupture scenarios, we chose GP.0.35 which has shallow slip, similar to that in Mod1. No attempt was made to select the GP2010 model that has the slip distribution closest to Mod1.

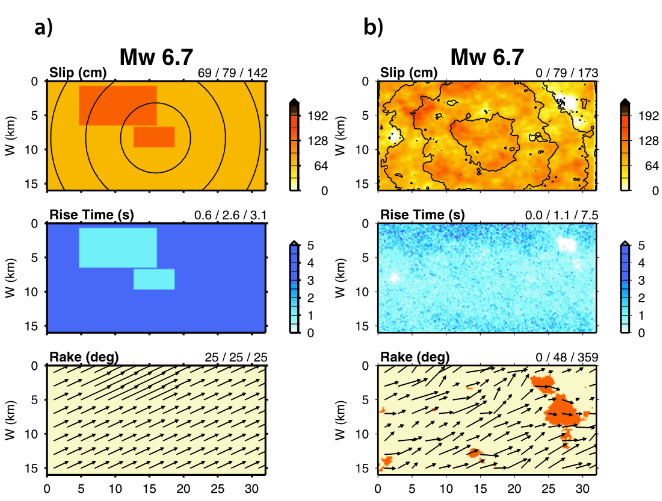

FIG.2. Kinematic rupture models for a M6.9 strike slip earthquake. a) produced with the IM2011 method. b)produced with the GP2010 method.

The spatial slip smoothness parameter used in generating GP.0.35 is **r**=0.35. A larger **r** produces a more heterogeneous spatial slip distribution. The effects of **r** on simulated ground motion will be discussed in a subsequent section. Figure 3 shows prescribed time histories of slip velocity at two selected locations, one inside the large asperity and the other in the background area for Mod1. The same locations were used for displaying the corresponding GP.0.35 slip velocity. Note that in the Graves and Pitarka hybrid ground motion simulation method the slip velocity function is only used in computing the low frequency part of the ground motion. As it will be demonstrated later, at these frequencies the effect of details in the shape of slip velocity functions is much smaller than that of other rupture parameters, such as asperities location, rupture speed, and rupture initiation location. The low-frequency part (0.1-2Hz) of ground motion was calculated using synthetic Green's functions computed with an FK method. Table 2 describes the flat-layered velocity model used in the simulations. The sub-faults dimensions used in the low frequency simulations were 0.2x0.2km, and those in the high frequency simulations were 2kmx2km. The crossover frequency between deterministic and stochastic parts of the simulated ground motion was set at 2Hz. Many studies have assumed that the transition between the deterministic and stochastic characteristics of ground motion occurs at 1Hz, partly due to computational limitations in wave propagation computation. However, we would expect that for the source contribution the transition between the coherent and incoherent summation vary with magnitude [21]. Figure 4 compares time histories of ground motion acceleration and velocity computed with both rupture models at 16 selected stations. Given the fact that no attempt was made to select a GP2010 slip model with characteristics that are the closest to Mod1, the similarities between the velocity and acceleration time histories produced with the two rupture models is impressive. The RotD50 [23] spectral acceleration goodness-of-fit plots for Mod1 and GP.0.35 averaged over all 32 stations is shown in Figure 5. The favourable comparison of the acceleration response spectra on a broad period range demonstrates that the rupture models produce equivalent ground motions.

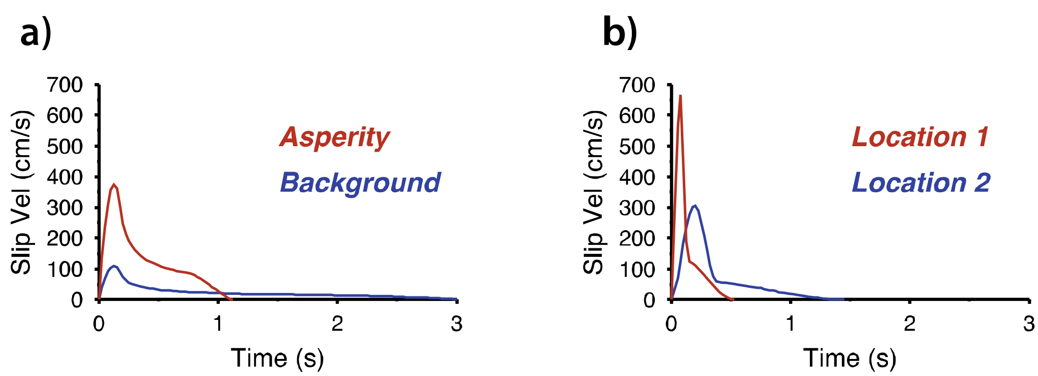

FIG. 3. Comparison of slip velocity functions in the asperity area (red trace) and background fault area (blue trace): a) IM2011 model, b) GP2010 model. Slip velocity functions in a) and b) are shown for the same locations on the fault

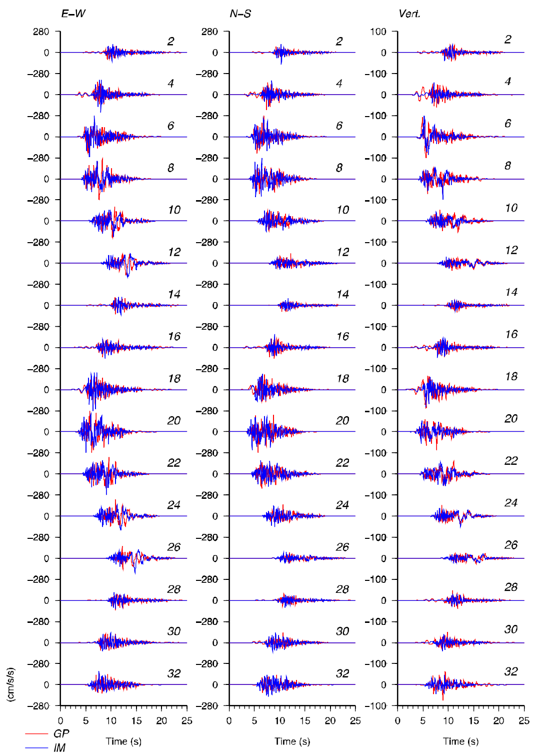

FIG. 4a. Comparison of broadband (0.1-10Hz) acceleration time histories simulated with the GP.0.35 (red traces) and Mod1 (blue traces) rupture models.

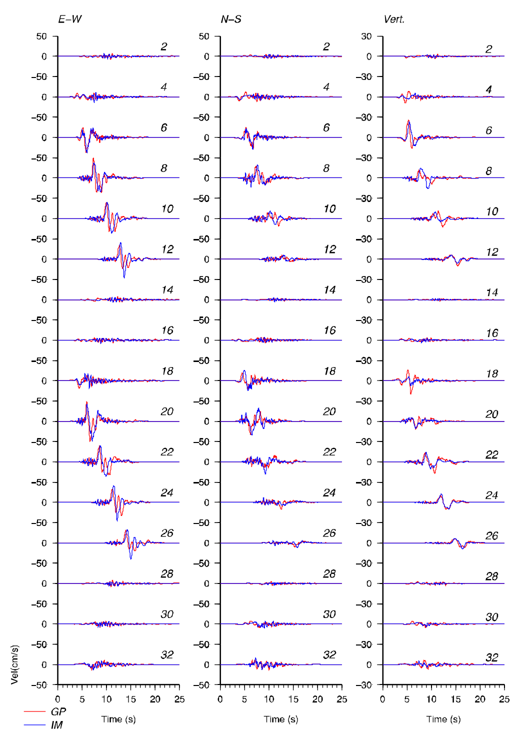

FIG. 4b. Comparison of broadband (0.1-10Hz) velocity time histories simulated with the GP.0.35 (red traces) and Mod1 (blue traces) rupture models. Stations name is indicated on the left of each trace.

The two rupture generators were further investigated by analysing the sensitivity of the simulated ground motion to asperities locations in the IM2010 models. We generated two additional rupture models, named Mod2, and Mod3, for which the asperities were gradually moved from the northern edge to the southern edge of the fault, respectively. The slip models and goodness–of-fit for Mod1, Mod2, and Mod3 with respect to GP.0.35 are shown in Figure 6. Moving the asperity areas from north to south of the rupture initiation affects the rupture directivity at most of the stations. As expected, rupture directivity has a strong effect at periods longer than 1s. Although to a much smaller extend, the asperity location also affects ground motion amplitudes at shorter periods, between 0.2-1s. In the IM2010 most of the high frequency ground motion is generated in the asperity area. Consequently, moving the asperities location can certainly produce the slight high frequency difference among models seen here. Regardless of differences in slip distribution the IM2011 and GP2010 rupture models implemented in the Graves and Pitarka simulation method produce ground motion with similar characteristics.

5. Discussion and Conclusion

The broadband simulations shown in this article were performed with the Graves and Pitarka method. In essence this hybrid method uses deterministic representations of rupture kinematics and wave propagation to produce the low frequency part of ground motion (usually frequencies < 1Hz), and heterogeneous rupture with stochastic small-scale perturbations and stochastic Green's functions to produce the high frequency part of the ground motion (usually frequencies > 1hz). This means that the high frequency part of the simulated ground motion is produced by contributions from both rupture process and wave propagation scattering. This is not exactly the case for Irikura and Miyake [1] method. In their method, because the slip distribution is simple, and slip is homogeneous within the asperity and background areas, the high frequency part of simulated ground motion variability is mainly produced by the 3D wave propagation scattering effects, carried by the stochastic Green's functions. Whereas the ground motion amplitude is mainly controlled by the asperity stress drop [16].

TABLE 1: FAULT PARAMETERS FOR A M6.5 EARTHQUAKE RUPTURE SCENARIO

Fault Parameter	
Fault Length	32 km
Fault Width	16 km
Depth to Top of Fault	3 km
Rupture Velocity	2.56 km/s
Strike	0^o
Dip	75^o
Rake	25^o

TABLE 2: 1D VELOCITY MODEL

Thickness (km)	**V_p (km/s)**	**V_s(km/s)**	**Density (g/cm^3)**	**Q_p**	**Q_s**
0.5	3.2	1.8	2.0	200	100
4.5	5.7	3.2	2.4	500	250
13.0	6.0	3.46	2.7	500	250
Half Space	6.7	3.87	2.8	1000	500

It is interesting to know how sensitive is the simulated ground motion to small-scale random variations of the IM2011 slip on the fault. The robustness of the IM2011 rupture generator associated with small-scale slip variability was tested by adding small-scale random heterogeneity to Mod1. The small-scale heterogeneity was introduced in the frequency wave (FK) number domain, by adding a K^2 spectral fall-off to the original FK slip spectrum of Mod1 for wavelengths longer than 5km. The new stochastic slip model named Mod1-Stoch retains the overall large-scale geometry of the original slip distribution and all other kinematic parameters of Mod1. The Mod1-Stoch and the goodness of fit of the acceleration response spectra computed with Mod1 and Mod1-Stoch are shown in Figure 7.

Both models produce very similar ground motion at all periods. This result suggests that the addition of small-scale heterogeneity to the entire fault area does not affect the simulated ground motion significantly. Simulations of recorded ground motion from large earthquakes in Japan, have indicated that enhanced heterogeneous stress drop within asperity areas could improve the method's overall performance [24], [9].

One important parameter of both IM2011 and GP2010 kinematic rupture models is the slip velocity function. Slip velocity time function reflects the kinematic energy release at a given point on the fault. The functional form of slip velocity function used in these models is derived by spontaneous rupture modelling on planar faults [25], [20]. The amplitude and duration of the first pulse in the slip velocity function (see Figure 2) are poorly resolved. In IM2010 the shape of the first pulse is controlled by f_{max} fixed at 5Hz. We investigated the effect of f_{max} on simulated ground motion by comparing two simulations made with Mod1

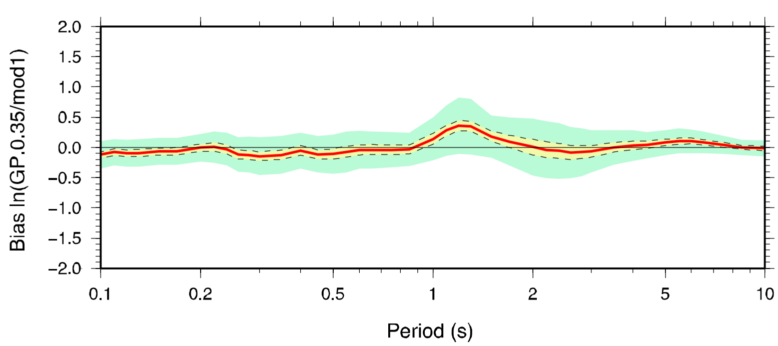

FIG. 5. Spectral acceleration goodness of fit for the M6.7 scenario earthquake simulations using the GP.0.35 and Mod1 rupture models.

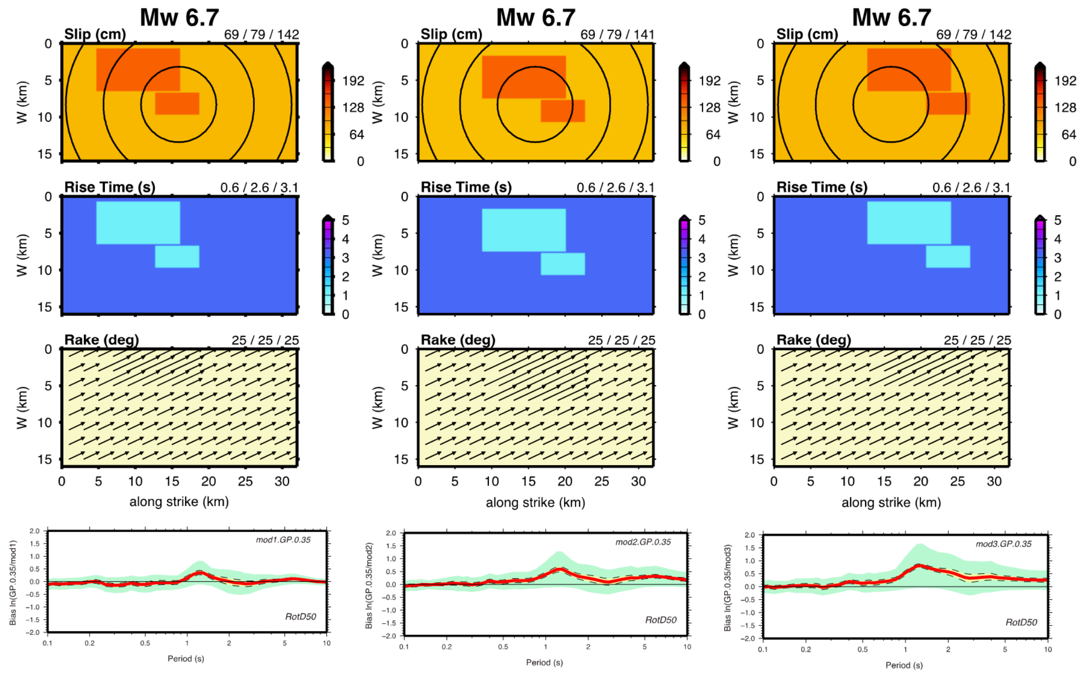

FIG. 6. Slip models Mod1, Mod2, Mod3 (top panels) and corresponding spectral acceleration goodness of fit for the M6.7 scenario earthquake simulations using GP.0.35 and Mod, Mod2, and Mod3 rupture models.

using f_{max} = 5Hz and f_{max} = 10Hz. The resulting slip velocity functions and the spectral acceleration goodness of fit between the simulations made with the two models are shown in Figure 8. In the simulations with Graves and Pitarka [2] method the effect of f_{max} used by IM2011 on ground motion is practically insignificant. Since the higher frequencies are computed using the stochastic approach, the change in the slip velocity function related to changes in f_{max} has little impact on simulations.

Results of sensitivity analysis of spatial slip smoothness parameter **r**, used in GP2010 rupture generator on simulated ground motion, are summarized in Figure 9. We compared ground motion simulated with GP.0.35 model, for which **r** = 0.35, and GP.0.85 model with a larger **r,** set at 0.85. Also shown in this figure are the corresponding rupture models. The acceleration response spectra goodness of fit between the two models suggests that a more variable slip distribution generates slightly larger ground motion in the period range of 1-4 s.

We concluded that when used in the hybrid method of Graves and Pitarka [2] the IM2011 and GP2010 rupture models for strike-slip earthquakes produce similar ground motion in a broad frequency range (0.1-10Hz). The addition of small-scale random heterogeneity in slip models produced with IM2011 has insignificant effect. In contrast, for GP2010 the spatial slip smoothness can have a more pronounced effect. The comparison between IM2010 and GP2010 in modelling ground motion from recorded earthquakes is the subject of the second phase of the study presented here.

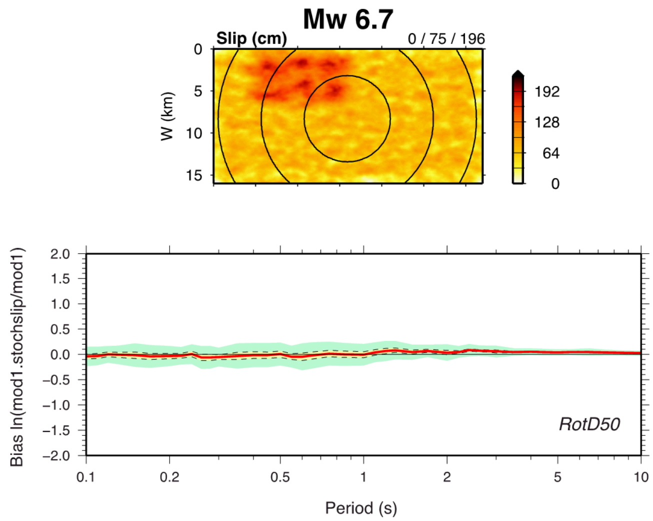

FIG.7. Slip model Mod1-Stoch (upper panel) and spectral acceleration goodness of fit between ground motion computed with Mod1 and Mod1-Stoch rupture models (bottom panel).

REFERENCES

[1] IRIKURA, K, MIYAKE, H., "Recipe for Predicting Strong Ground Motion from Crustal Earthquake Scenarios", Pure Appl. Geophys. 168, (2011) 85-104.

[2] GRAVES, R., PITARKA, A. "Broadband Ground-Motion Simulation Using a Hybrid Approach", Bull. Seism. Soc. Am., 100(5A), (2010) 2095-2123, doi: 10.1785/ 0120100057.

[3] KAMAE, K., IRIKURA, K., PITARKA, A. "A technique for simulating strong ground motion using hybrid Green's function", Bull Seism. Soc. Am. 88, (1998) 357–367.

[4] PITARKA, A., SOMERVILLE, P., FUKUSHIMA, Y. "Ground-motion attenuation from the 1995 Kobe earthquake based on simulations using the hybrid Green's function method", Bull. Seism. Soc. Am., 92, (2002) 1025-1031.

[5] MIYAKE, H., IWATA, T., IRIKURA, K., "Source characterization for broadband ground-motion simulation: kinematic heterogeneous source model and strong motion generation area", Bull. Seism. Soc. Am. 93, (2003) 2531–2545.

[6] PITARKA, A., SOMERVILLE, P., FUKUSHIMA, Y., UETAKE, T., IRIKURA, K. "Simulation of near-fault strong ground motion using hybrid Green's functions", Bull. Seism. Soc. Am., 90, (2000) 566-586.

[7] MORIKAWA, N., SENNA, N., HAYAKAWA, Y., FUJIWARA, H. "Shaking maps for scenario earthquakes by applying the upgraded version of the strong ground motion prediction method ''Recipe'', Pure Appl. Geophys. (2010) doi:10.1007/s00024-010-0147-4.

[8] PITARKA, A., MATSUZAKI, S., WATANABE, T., COLLINS, N., GRAVES, R., SOMERVILLE, P., "Rupture Model for a Characterized Intraslab Earthquake" (Proceedings of the 15th Word Conference of earthquake Engineering, September 24-28, Lisbon, Portugal, 2012).

[9] KURAHASHI, S., IRIKURA, K., "Short Period Source Model of the 2011 M_w 9.0 Off the Pacific Coast of Tohoku Earthquake", Bull. Seism. Soc. Am., 103, (2013) 1373-1393, doi:10.1785/0120120157.

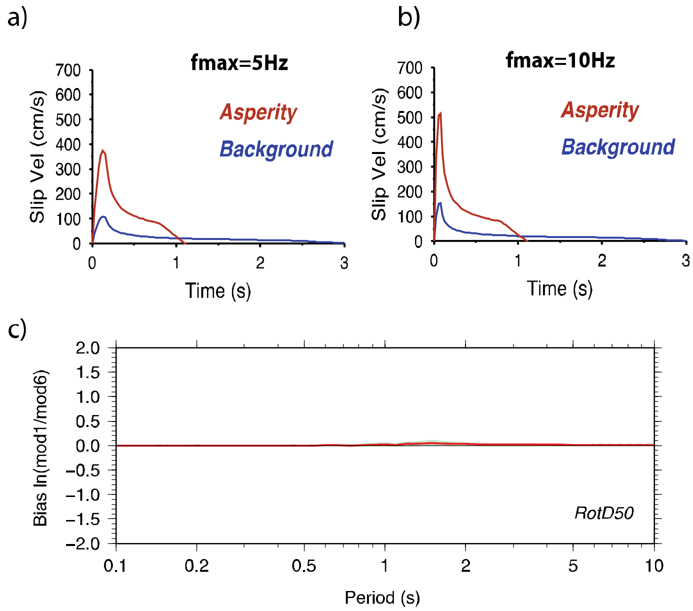

FIG. 8. a) IM2011 slip velocity functions computed with fmax= 5Hz. b) IM2011 slip velocity functions computed with fmax= 10Hz. c) Spectral acceleration goodness of fit between ground motion computed with Mod1 with fmax=5Hz and Mod1 with fmax=10Hz.

[10] MAECHLING, P. J., SILVA, F., CALLAGHAN, S., JORDAN, T. “SCEC Broadband Platform: System Architecture and Software Implementation”, Seismol. Res. Lett., 86, 1, (2015) doi: 10.1785/0220140125.

[11] OLSEN, K., TAKEDATSU, R. “The SDSU Broadband Ground-Motion Generation Module BB toolbox Version 1.5”, Seism. Res. Lett., 86, (2015), 81-88, doi:10.1785/0220140102.

[12] SCHMEDES, J., ARCHULETA, R., LAVALLE, D. “Correlation of earthquake source parameters inferred from dynamic rupture simulations”, J. Geophys. Res., 115, B03304, (2010), doi: 10.1029/2009JB006689.

[13] DAS, S., KOSTROV, B. “Fracture of a single asperity on a finite fault”, In Earthquake Source Mechanics. Geophysical Monograph 37, Maurice Ewing Series 6, American Geophysical Union, (1986), 91–96.

[14] SOMERVILLE, P., IRIKURA, K., GRAVES, R., SAWADA, S., WALD, D., ABRAHAMSON, N., IWASAKI, Y., KAGAWA, T., SMITH, N., KOWADA, A. “Characterizing earthquake slip models for the prediction of strong ground motion”, Seism. Res. Lett. 70, (1999) 59–80.

[15] DALGUER, L. A., MIYAKE, H., IRIKURA, K. “Characterization of dynamic asperity source models for simulating strong ground motions”(Proceedings of the 13th World Conference on Earthquake Engineering No. 3286), (2004).

[16] DAN, K., WATANABE, M., SATO, T., ISHII, T. “Short- period source spectra inferred from variable-slip rupture models and modelling of earthquake fault for strong motion prediction”, J. Struct. Constr. Eng. AIJ 545, (2001) 51–62.

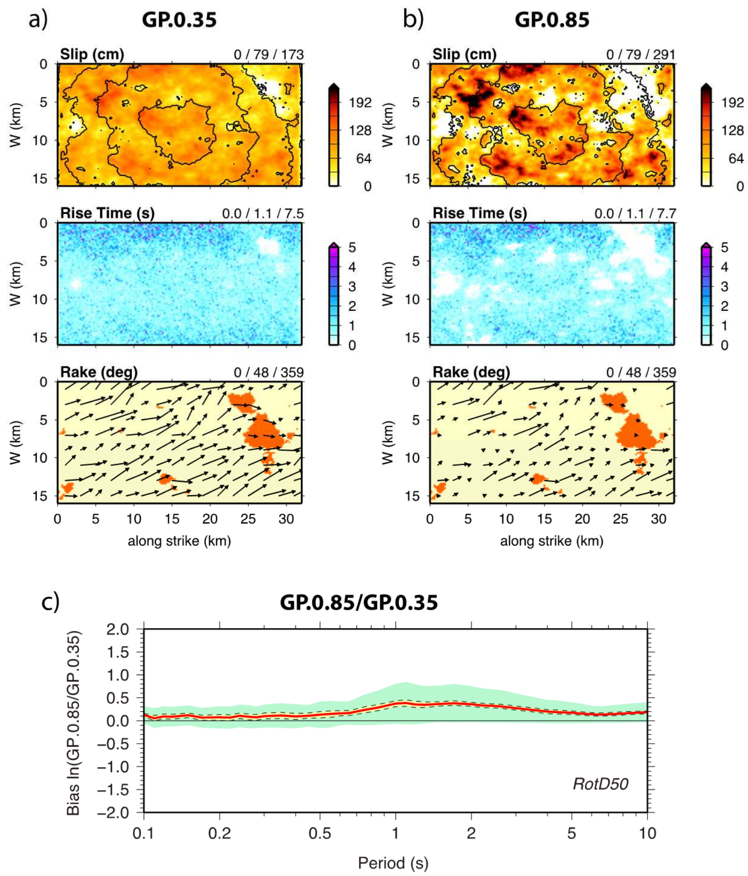

FIG. 9. a) GP.0.35 rupture model generated with rupture smoothness r=0.35. b) GP.0.85 rupture model generated with rupture smoothness r=0.85. c) Goodness of fit of ground motion spectral acceleration simulated with model GP.0.85 and GP.0.35 for an M6.7 scenario earthquake.

[17] IRIKURA, K, MIYAKE, H.," Prediction of strong ground motions for scenario earthquakes", Journal of Geography 110, (2001) 849–875 (in Japanese with English abstract).

[18] IRIKURA, K., MIYAKE, H., IWATA, T., KAMAE, K. KAWABE, H. "Revised recipe for predicting strong ground motion and its validation", (Proceedings of the 11th Japan Earthquake Engineering Symposium, 2002) 567–572 (in Japanese with English abstract).

[19] IRIKURA, K. "Recipe for predicting strong ground motion from future large earthquake", Annuals of Disaster Prevention Research Institute, 47A, (2004) 25–45 (in Japanese with English abstract).

[20] NAKAMURA, H., MIYATAKE, T. "An approximate expression of slip velocity time functions for simulation of near-field strong ground motion", Zisin 53, (2000) 1–9 (in Japanese with English abstract).

[21] FRANKEL, A. "A constant stress-drop model for producing broadband synthetic seismograms: comparison with the Next Generation Attenuation relations". Bull Seism. Soc. Am., 99, (2009) 664–680

[22] GRAVES, R., PITARKA, A. "Refinements to the Graves and Pitarka (2010) Broadband Ground Motion Simulation Method". Seism. Res. Lett., 86, (2015) 75-80, First published on December 17, 2014, doi:10.1785/0220140101.

[23] BOORE, D. WATSON-LAMPREY, Watson-Lamprey, J., ABRAHAMSON, N.

"Orientation-independent measures of ground motion", Bull. Seism. Soc. Am. 96, (2006) 1502-1511.

[24] PITARKA, A., SOMERVILLE, P., FUKUSHIMA, Y. "Ground-motion attenuation from the 1995 Kobe earthquake based on simulations using the hybrid Green's function method". Bull. Seism. Soc. Am., 92, (2002) 1025-1031.

[25] DAY, S. M. "Three-dimensional simulation of spontaneous rupture: the effect of nonuniform prestress", Bull Seism. Soc Am., 88, (1982) 512–522.